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Evidence for compact structuring in the corona of active stars

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Abstract.

The “current wisdom” regarding the structuring of the X-ray emitting corona in active stars (i.e. a corona dominated by extended coronal structures) is briefly reviewed, followed by a review of a new approach to flare analysis and the analysis of a significant number of newly observed and previously published large flares, all leading to a much more compactly structured corona. Recent observations showing the polar location of the flaring plasma are then discussed, showing how the current evidence points toward a (flaring) corona composed of rather low-lying polar structures, also in agreement with some recent radio VLBI observational results and with starspot Doppler images. The resulting picture is significantly different from the solar case.

1. Introduction

Active late-type stars have a coronal X-ray luminosity of up to $\geq 10\,000$ times higher than the Sun; it is thus natural to ask whether the structuring of such a corona can be simply understood as a simple extension of the solar case or not. Under structuring here we mean the size, location and type of the coronal structures responsible for the bulk of the observed emission measure at X-ray wavelengths (i.e. plasma at MK temperatures). For the Sun, high-resolution X-ray images of the corona have allowed a detailed study of its spatial structuring, showing a corona structured in magnetic loops confined to intermediate latitudes, with ample coronal holes specially at the solar poles. The typical maximum height of the corona above the photosphere is well below the solar radius. Can this corona be scaled to one 10 000 times more luminous, and if so, how?

Stars are unresolved objects and therefore only indirect evidence can be obtained about the spatial size, location and structuring of their corona. Three basic types of observations can be used to derive structural information about the corona, namely 1) the analysis of flare decay, 2) the modulation of light due either to mutual eclipses in a binary system or to self-eclipse due to stellar rotation in a single star, and 3) the determination of plasma densities from high-resolution spectra.

Here we briefly review the above approaches, showing that in many cases the results have been interpreted, in the past, as giving evidence for a large, rather diffuse corona. We then proceed to discuss recent developments in the

methodology as well as in the observations, and discuss how these new development convincingly point toward a picture of a rather compact corona, located on (or near) the poles of active stars.

2. Methodology

2.1. Flare decay analysis

The analysis of the decay of flares can offer insights in the size and characteristics of the flaring structures, and indeed it has often been used in this way. Perhaps the most widely used approach for the analysis of the decay of flaring loops has been the so-called quasi-static approach (van den Oord & Mewe 1989), which assumes that the heated loops decay through a sequence of quasi-static states; while the theoretical framework of the method includes sustained heating as a free parameter, in practice its application has never given any indication for the presence of heating during the decay phase. As a consequence, when applied to the study of long-lasting intense flares the approach always results in long, low-density loops, which minimize both conductive and radiative losses, allowing the plasma to cool slowly and thus justifying the observed long decay times.

Another approach used at times has been the so-called two-ribbon approach of Kopp & Poletto (1984), which however requires a priori assumptions on the spatial structure and thus is of limited applicability in the stellar case.

More recently, an approach based on hydrodynamic modeling of the decaying loops has been developed by Reale et al. (1997); this approach uses the slope of the decay in the temperature-density plane as an explicit diagnostic for the presence of sustained heating, and has been tested on the Sun, showing that many apparently “impulsive” solar flares are actually dominated by sustained heating in the decay phase. As a consequence, this approach results in the majority of cases in smaller loops than the quasi-static approach.

One important point is that only intense (i.e. pathological in solar terms) stellar flares yield sufficient statistics to allow a detailed study, so that analogies with the solar case should be treated with some caution, and deductions made on the Sun may or may not be a good proxy for the stellar case. A significant number of intense events has been observed by e.g. *Einstein*, EXOSAT, ROSAT, ASCA and SAX. Up to until ca. 1998 they have almost always been modeled with the quasi-static approach, with the resulting model invariably pointing to the presence of long loops. An example of some literature results regarding the quasi-static analysis of large stellar flares is shown in Table 1.

The purported very long loops populating the coronae of active stars have led to a picture of an extended corona, which in some cases have been pictured as extending between the components of binary systems (e.g. the picture of Uchida & Sakurai 1983), which has at times been dubbed “the standard model”.

2.2. Eclipse mapping

A spatially inhomogeneous corona will, when subject to the eclipse from a companion, or to self-eclipse from the photosphere of the parent star, produce a modulated light curve, which in principle could be used to deduce its structure. The derivation of spatial information from the observed light curve of either sin-

Table 1. Examples of some well known stellar flares. L is the length of the structure obtained with the quasi-static approach.

Star	Instrument	L	Star	Instrument	L
Algol ³	PSPC	$\simeq 2.0 R_*$	EV Lac ¹	PSPC	$\simeq 10 R_*$
Algol ²	EXOSAT	$\simeq 0.6 R_*$	YLW 15 ⁷	ASCA	$\simeq 3.0 R_*$
Algol ⁴	GINGA	$\simeq 2.5 R_*$	LkH α 92 ⁸	PSPC	$\simeq 1.0 R_*$
AR Lac ⁶	PSPC	$\simeq 1.3 R_K$	V773 Tau ⁹	ASCA	$\simeq 1.2 R_*$
CF Tuc ⁵	PSPC	$\geq 2.7 R_K$			

¹Schmitt (1994), ²van den Oord et al. (1986), ³Ottman & Schmitt (1996), ⁴Stern et al. (1992), ⁵Kürster & Schmitt (1996), ⁶Ottman & Schmitt (1994), ⁷Tsuboi et al. (2000), ⁸Preibisch et al. (1993), ⁹Tsuboi et al. (1998).

gle or binary stars is a process ripe with uncertainty, which makes a number of assumption (e.g. that all observed variations are eclipse-induced, and not due to the temporal variability of the emission) which are very fragile in the presence of observational noise. The difficulties and significant limitations of the approach have been discussed in detail by e.g. Schmitt (1998). Nevertheless, a number of such analyses have appeared in the past in the literature, notably on AR Lac (e.g. White et al. 1990; Siarkowski et al. 1996); these have produced evidence for large emitting regions, with the inter-binary region filled with plasma. However, as the same authors also point out, other solutions are equally possible (including a quite compact corona) if different a priori constraints are assumed.

More in general, the observed lack of strong eclipses (e.g. on Algol) has been interpreted as also pointing to the presence of very large structures (loops), sufficiently larger than the parent star that only a small fraction can be occulted at each given time, and thus in agreement with the very large loops derived by flare decay analysis through the quasi-static method. This view has contributed to a general picture of active stellar coronae as quite extended objects.

The interpretation of light curves from active eclipsing binaries is complicated by the difficulty of disentangling the contribution to the light curve from each component. Binary systems with an X-ray active star and a X-ray dark companions are indeed much better targets for this type of studies, as the X-ray dark star acts as a pure occulting disk. Examples of this type of stars are the Algol-type systems. A pioneering study of such a system has been performed by Schmitt & Kürster (1993): the clear observation of a sharp X-ray eclipse on α CrB (a G5V+A0V system, $0.9 + 3.0 R_\odot$, $L_X \simeq 100 L_{X\odot}$) clearly indicates that the coronal structures on the G5V star are compact, significantly smaller than the star itself, with no evidence for extended structures.

3. New observations of large stellar flares

An observational breakthrough in the study of the structuring of coronae in active stars was achieved in 1997 with a long observation of Algol (a B8V+K3IV with a quiescent X-ray luminosity of $L_X \simeq 5000 L_{X\odot}$) performed with the SAX observatory. The observation was dominated by a long-lasting (ca. 2 d), intense flare, which underwent a total eclipse when the B-type star passed in front of the K-type star. This allowed Schmitt & Favata (1999), for the first time, to determine the size and location of an individual coronal structure (the flaring “loop”)

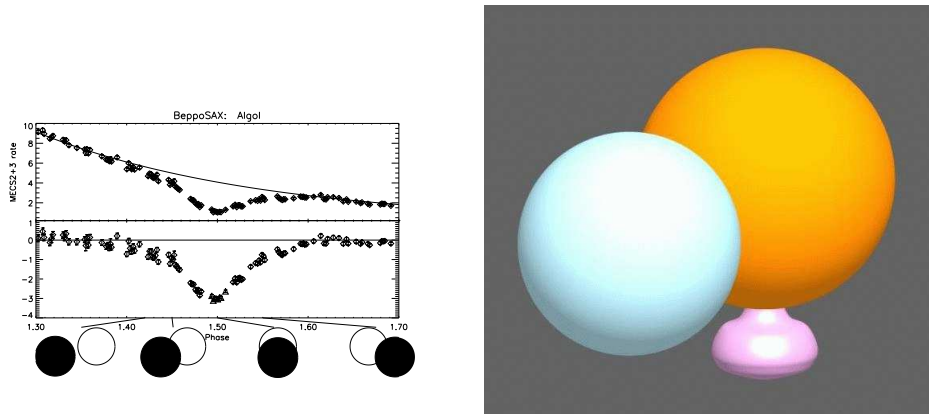


Figure 1. The light curve of the SAX Algol flare eclipse is shown in the left-hand panel, together the relative position of the two stars. The right-hand panel shows the region (on the south pole of the K star) to which the flaring plasma must be confined to produce the observed eclipse light curve.

in a deterministic way (without the ambiguities present in active binaries). The results were surprising, in that the flaring structure is rather compact (with a maximum height $H < 0.6 R_*$) and located on the south pole of the K-type star. Both the size and location of the flaring structure are very different from the “classic” picture: there is no evidence for extended structures nor for (near-) equatorial structures. In addition, to allow for such a long-lasting event to take place in a compact structure, the plasma must be heated throughout the decay (else the natural decay time would be much faster than the observed one).

The excellent temporal coverage and statistics of this event have also allowed Favata & Schmitt (1999) to perform a detailed “comparative test” of different flare-decay methods, for the first time having a “ground truth” against which the reliability of the method could be assessed. The result is that the quasi-static method, when applied to this event, overestimates the loop size by almost an order of magnitude and fails to detect the presence of sustained heating. The hydrodynamic method, on the other hand, properly diagnoses that the loop must be heated during the decay, and thus predicts a smaller loop size, closer to the ground truth (although still somewhat too large).

3.1. A critical reassessment of the Algol corona

Armed with the knowledge that the quasi-static method is likely to consistently overestimate the size of the flaring structures, and that the hydrodynamic method supplies a much better estimate, a systematic re-analysis of all known large flares on Algol was performed by Favata et al. (2000b). A summary of the results is shown in Table 2. The key result of this work shows that in all cases strong sustained heating is present, and that the flares are always relatively low-lying, with no evidence for very long, extended loops. This is in contrast with the results originally obtained with the quasi-static method, which claimed

long loops and in all case freely decaying flares with no evidence for sustained heating.

Table 2. A summary of the reanalysis of the Algol flares performed by Favata et al. (2000b). The observed peak temperature (T_{\max}) and decay times are reported (τ_{LC}), followed by the ratio between the observed and intrinsic heating time ($\tau_{\text{LC}}/\tau_{\text{th}}$, indicating the importance of sustained heating), and by the length obtained with the quasi-static method (L_{QS}) and with the hydrodynamic analysis (L_{Hy}). For the SAX flare, the geometric size is also indicated.

Instr.	T_{\max} MK	τ_{LC} ks	$\tau_{\text{LC}}/\tau_{\text{th}}$	L_{QS} R_*	L_{Hy} R_*	L_{geom} R_*
EXOSAT	78	5.3	2.4	0.6	0.3 [0.2 0.4]	—
GINGA	67	19.8	4.2	2.4	0.5 [0.4 0.6]	—
ROSAT	44	30.2	2.6	2.0	1.2 [1.1 1.3]	—
SAX	142	49.6	2.4	7.0	3.3 [1.9 4.7]	0.9

3.2. Other examples: flare stars

A similar type of analysis, with a consistent analysis of all known flaring events, was performed by Favata et. al (2000a) on the “prototypical” flare star AD Leo. The significant number of events studied, across different instruments and detectors, allows to deduce some general conclusions: the characteristic size of the flaring structures is small, well below the stellar radius, and vigorous sustained heating is in essentially all cases present. The characteristic loop size is, for AD Leo, even smaller than for Algol, with a characteristic size of $L \simeq 0.3R_*$.

Also, an exceptional flare (whose total energy was, at peak, as large as the stellar photospheric luminosity) was detected with ASCA on the flare star EV Lac (see Fig. 2). Notwithstanding the exceptional intensity of the event, the hydrodynamic analysis (Favata et al. 2000d) of the event shows that, similarly to the Algol SAX flare, the flaring plasma is confined to a region $L \leq 0.5 R_*$, and that the decay light curve is also dominated by the time evolution of the sustained heating.

3.3. Other examples: active binaries

Similar conclusions have been reached (Favata et al. 2001) on active binaries through the analysis of some well-known events previously studied in the literature. For example, for the flare observed by ROSAT on AR Lac (Ottmann & Schmitt 1994) a quasi-static analysis yields a size larger than the K star in the system; this is reduced to $L \leq 0.5 R_*$ when analyzed with the hydrodynamic method. Similarly, the long and intense event observed by ROSAT on CF Tuc (Kürster & Schmitt 1996) for which the quasi-static analysis yields a size for the flaring region of $L \simeq 3 R_*$ is reduced to $L \leq R_*$ by the hydrodynamic analysis. Once more, the decay of these large flaring events is dominated by the presence of vigorous sustained heating.

3.4. Other examples: pre-main sequence stars

A re-analysis of large flaring events on pre-main sequence (PMS) stars (Favata et al. 2000c) also shows that sustained heating during the decay phase is a common feature and that the size of the flaring regions obtained with the hydrodynamic analysis is significantly smaller than the one obtained previously with the quasi-static approach. In general, the “larger than the star” loops found by the quasi-static analysis are reduced to “smaller than the star” structures. This applies to different categories of PMS stars; for the ASCA flares on the proto-star (YSO) YLW 15 the analysis of Tsuboi et al. (2000) found a large loop ($L \simeq 3 R_*$), which is reduced to $L \leq R_*$ by the hydrostatic analysis. Similarly, for the flare observed on the classical T Tau star (CTTS) LkH α 92 by Preibisch et al. (1993) the size shrinks from 1 to $0.5 R_*$, while for the ASCA flare on the weak-line T Tau (WTTS) star V773 Tau (Tsuboi et al. 1998) the size shrinks from 1.2 to $0.3 R_*$. Finally, an analysis with the hydrodynamic method of the ROSAT flare on the WTTS HD 283572 reported by Stelzer et al. (2000) yields a size for the flaring structure of $\simeq 0.4 R_*$. Also, an analysis with the same approach of the “twin” large flares observed by SAX on the zero-age main sequence (ZAMS) star AB Dor (Maggio et al. 2000) consistently results in structures well below the stellar size. In general, the consistent small size found for the flaring structures on PMS stars casts a doubt on the reality of the magnetic structures extending from the star to the accretion disk which have been invoked (e.g. Montmerle et al. 2000) to explain the events on YSO’s and CTTS’s. The general characteristics of these events are indistinguishable from the ones taking place on single main sequence stars (e.g. on AB Dor), thus pointing toward similar coronal structures being present in both cases.

4. Discussion

4.1. Size of flaring structures

The wealth of new observations (and re-analysis of existing observations) discussed above shows consistently that application of the hydrodynamic method (whose superiority was clearly shown on the Algol SAX flare) results in much smaller structures than the ones obtained with the quasi-static analysis (whose failure at detecting sustained heating was, again, shown on the Algol SAX flare) of the same events. In general, all flaring structures are smaller than the size of the star, with sustained heating being a common feature. The size of the flaring coronal structures derived with hydrodynamic modeling are in general, by solar standards, large, but not “exceptional”. The presence of strong sustained heating makes it likely that even the hydrodynamic method actually over-estimates the size of the coronal structures, so that, if anything, the actual size is likely to be even smaller. These conclusions apply to active stars spanning a wide range of mass, sizes and evolutionary stages.

4.2. Time-profile of the sustained heating

One consequence of the presence of sustained heating during the decay of flares is that the observed light curve is dominated by the time-profile of the heating process and does not reflect the actual structure of the flaring structure. Thus,

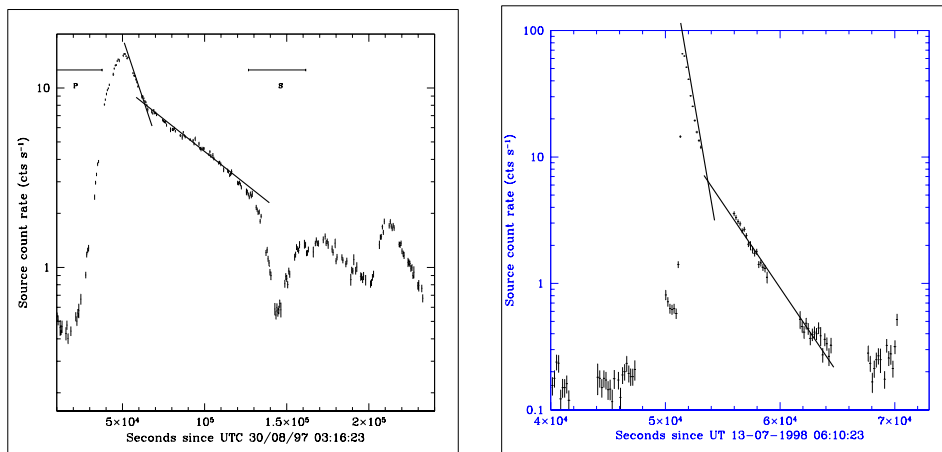


Figure 2. The decay light curve of the SAX Algol flare (left-hand panel) and of the ASCA EV Lac flare (right-hand panel) showing in both cases an initially steep decay followed by a slower phase.

(repeated) features in the decay light curve should provide hints to the flare heating mechanism. One feature which appears to be consistently present in intense flares (when the temporal resolution and the S/N are sufficient) is the presence of a “knee” in the decay light curve: the initial (exponential) decay is fast, and it slows down significantly in the second part of the event. This is apparent, e.g. in the two events shown in Fig. 2. Similar features are visible in intense solar events.

4.3. Location of the flaring plasma

The (circumstantial) evidence about the location of the flaring plasma available prior to the Algol SAX flare has in general been interpreted as pointing toward structures located at low stellar latitudes. The two key lines of evidence used for this argument have been the results of the light-curve deconvolution and the long duration of large flaring events.

Light curve deconvolution of active binaries (e.g. Siarkowski et al. 1996) results mostly in coronal structures located at low latitudes (near-equatorial structures); however, as discussed for the size of the coronal structure, the results are quite sensitive to the a priori constraints assumed, so that it is unclear whether solutions with (predominantly) high-latitude structures would be equally possible.

Intense stellar flares often have a duration comparable to (or even longer than) the stellar rotational period (or the orbital period in the case of binary systems). The lack of observed self (or mutual) eclipses of these long events, coupled with the inference (from quasi-static analyses) that the flaring structures were very large, had led to the deduction that they were likely located close to the system’s equator. The large size was used to justify the observed lack of eclipses. The observed eclipse of the Algol SAX flare, together with the evidence for predominantly compact flaring structures discussed above, shows that these deductions are unlikely to be correct. The Algol flare results from a

polar structure, and a polar location is also compatible (and indeed necessary) to explain many other flare observations. The flares observed with SAX on AB Dor by Maggio et al. (2000) last for a time comparable to the stellar rotational period, and yet the flaring structures are small and are not self-eclipsed. This can only be explained if the flaring structures are located on the (exposed) stellar pole, so that they are never eclipsed, even if small in size. A similar argument can be used to explain other similar events: the very long-lasting flare observed by ROSAT on the flare star EV Lac (Schmitt 1994) lasts for more than one stellar rotation, yet it is not self-eclipsed. Given that even much more intense flares (e.g. the ASCA event studied by Favata et al. 2000d) on the same star can be easily explained as confined in small structures, once more only a polar location can explain the observed lack of self-eclipses. Similarly, the ASCA flares observed on the YSO YLW 15 last for a time comparable with a rotational period, yet they appear to be confined in small regions and not self-eclipsed. Again, a polar location appears to be the only one possible. One observation of YLW 15 (Tsuboi et al. 2000) three flares have been seen with a recurrence time comparable to the stellar rotation period. This has been interpreted as due to rotational modulation of the magnetic field stress; no rotational modulation of the light curve (as due to self-eclipse) is however visible. Such interpretation is thus not per se in contradiction with a polar location of the flaring plasma.

A (predominantly) polar location can also naturally explain the modest amounts of modulation observed in active binaries, and is compatible with the predominantly photospheric polar large spots deduced by Doppler imaging. Some theoretical models indeed predict that, for rapid rotators, the poles are the preferential location for the emergence of magnetic flux.

Interestingly, recent radio VLBI observations of Algol by Mutel et al. (1998) show that the (radio) flaring corona is also coming from two polar lobes with characteristic sizes smaller than the size of the K star in Algol, while the quiescent emission comes from a somewhat more extended region, comparable in size to the star, although also located on the polar regions. As shown by Favata et al. (2000b), a similar structure for the X-ray active corona can also explain the known characteristics of the X-ray emission. However, the polarization of the radio emission shows that the large scale field is likely bipolar, so that the solar-like “loop” picture may be inappropriate for the Algol corona (as well as for other high-activity ones), and that different type of magnetic structures may be necessary to confine the plasma.

5. Conclusions

The large body of observational evidence presented here (and accumulated mostly in the last two years) shows that the active (flaring) component of the corona of active stars is confined in structures which are significantly smaller than the star itself, and which are likely located at high stellar latitude. This is in contrast with the picture of very long, near-equatorial coronal structures (even with interconnecting loops in the case of active binaries, e.g. Uchida & Sakurai 1983) which has in the past been proposed to describe active coronae. Independent evidence for material at significant distance from the stars, and in the inter-binary region comes from Doppler mapping done e.g. with IUE observations (Pagano

et al. 2000, on AR Lac), using chromospheric lines. Such evidence is not in contrast with the picture presented here, given that the two concern material at very different temperatures, and thus likely not co-located: the flaring coronal plasma discussed here is mostly at temperatures of several MK to several tens of MK, while the chromospheric material whose presence is deduced through Doppler analysis (using e.g. Mg II lines) is at temperatures $T \leq 10^5 K$. Similar considerations apply to the evidence for large structures orbiting the young star AB Dor obtained by Collier Cameron et al. (1990): also in this case, the material detected is at much cooler temperatures than the coronal material responsible for the X-ray (flaring) emission, and thus unlikely to be spatially coincident with it.

The polar location of the flaring plasma is in stark contrast with the solar case, where active regions are confined to low and intermediate latitudes. This (together with the evidence from the radio observations of a largely dipolar field) points to a magnetic field structure, in the case of active stars, significantly different from the solar one, and thus also possibly to a different dynamo. Therefore, for the very active stars, the solar analogy may have to be considered with some caution, and the coronal structures responsible for the bulk of the (flaring) X-ray emission may indeed look different than in the Sun.

The paradigm of a compact (and polarly located) corona in active stars is also supported by the EUVE observations of contact (W UMa-type) binaries, for which high density is deduced from spectroscopy (and thus small volumes) for the emitting plasma, and the lack of strong orbital modulation (as well as the period difference with respect to the orbital motion, Brickhouse & Dupree 1998 on 44 Boo) also point to a polar compact corona. The upcoming flow of grating spectral observations of active stars from Chandra and XMM-Newton will likely put to test the picture presented here: spectroscopic observations of the decay of an intense flare, once achieved, would allow to independently measure the density and compare it with the one deduced from the hydrodynamic method used here. The “holy grail” for the field of coronal structuring would however be a grating observation of an event similar to the SAX Algol one.

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